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How will sectoral coverage affect the efficiency of an emissions trading system? A CGE-based case study of China

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HIGHLIGHTS

- This study investigates the importance of sectoral coverage in designing an ETS in China.
- The study uses a dynamic CGE model with disaggregated electricity technologies.
- The cost of INDC targets through the proposed eight-sector ETS is 10.5% GDP in 2030.
- GDP losses can be reduced to 3.3% by covering another 24.8% of emissions in ETS by 2030.
- Air pollution co-benefits of China's INDC can be as large as 136.7 billion USD in 2030.

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ABSTRACT

This study contributes to the existing literature on optimal carbon mitigation policy by quantifying the impacts of various sectoral coverage options for the emissions trading systems (ETS) used to achieve China's Intended Nationally Determined Contribution (INDC) targets for the Paris Agreement on climate change. The CHEER model, a computable general equilibrium (CGE) model of China with detailed representation of electricity and other energy intensive sectors, as well as a complete CO_2 emissions accounting module and carbon market, is used in this study. Results show several important findings. First, China's INDC targets can be achieved through an economy-wide ETS at an economic cost of 2.1% of real GDP by 2030. Second, including only the eight sectors proposed for initial implementation of the ETS in China is likely to result in a much larger mitigation cost than the economy-wide approach, estimated to be as high as 10.5% of 2030 real GDP. Thirdly, this study further indicates that the mitigation costs can be reduced to 3.3% of real GDP in 2030 if other energy-intensive sectors, accounting for additional 24.8% of total emissions, are included in the ETS. As a result, not all sectors are required to get close to the first-best mitigation option so long as critical sectors are not excluded. In addition, the temporal dimension of mitigation costs and air pollution co-benefits under different sectoral schemes of China's ETS gives policy-makers a degree of short-run flexibility in terms of phasing in additional industries over time.

1. Introduction

As the largest national emitter of greenhouse gas emissions (GHGs), China has emerged as a critical actor in efforts to combat global climate change. Beginning with its commitments in 2009 at the Copenhagen Climate Change Conference, China has developed a national strategy for reducing greenhouse gas emissions, which involves both emissions reduction targets and the development of low-carbon energy resources. China's initial commitment in 2009 was to reduce its CO_2 intensity (emissions per unit of economic output) by 40–45% below 2005 levels and increase the share of non-fossil primary energy consumption to 15% by 2020. Leading up the Paris Climate Change Conference in 2015, China extended the timeline to achieve its goals to 2030, committing to peak its CO_2 emissions by 2030 and increase its non-fossil primary energy consumption share to 20%. China's Intended Nationally Determined Contributions (INDCs), submitted in June of 2015, included these commitments as well as an additional commitment to reduce its CO_2 emissions intensity by 60–65% below 2005 levels by 2030.

Emissions trading systems (ETS) are widely considered to be a cost-effective emissions mitigation instrument [1] and have become an

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increasingly popular policy mechanism, with more than half of all countries expressing an interest in carbon markets as part of their INDCs [2]. China's interest in developing a CO_2 ETS dates back to the 12th Five Year Plan (2011–2015), established several regional ETS pilot programs. In June 2013, the city of Shenzhen implemented the first ETS pilot, followed by two provinces (Hubei and Guangdong) and four other cities (Beijing, Tianjin, Shanghai, and Chongqing). As of September 2016, the accumulated trading volume of CO_2 emissions permits in these seven pilots was 120 million tonnes CO_2 with a market value of 3.2 billion RMB (approximately US$4/tonne). In January 2016, the National Development and Reform Commission of China (NDRC) announced that the local and regional ETS pilots would be replaced by a national ETS in 2017. This national carbon market will be a central pillar of China's GHG mitigation policy portfolio.

Under the first-best, or optimal, ETS design, in which all emissions in the economy are covered [3,4], emitters decide whether to reduce emissions in their sectors or purchase permits from other emitters in a manner that equates the economy-wide carbon abatement costs with the market price of a permit. However, due to the political and administrative constraints [5], most existing emissions trading systems do not have full sectoral coverage and therefore operate in a second-best policy setting where only certain major emitters are covered under the ETS policy. For example, as currently implemented, the European Union's Emissions Trading System (EU-ETS), which is both the cornerstone of the EU's climate mitigation strategy and the largest ETS in the world, only covers electric power generation and several energy-intensive industries [6]. Similarly, China's proposed national carbon market will only include a limited number of emissions-intensive industries. So far, eight energy-intensive sectors (petrochemicals, chemicals, construction materials, iron and steel, non-ferrous metals, paper, electricity, and air transport) are likely to be covered by the proposed national carbon market [7].

An increasing number of studies have examined the design and impacts of national emissions trading systems. Defining the sectoral coverage should be the first priority when developing an ETS [8]. The allowance price, trading volumes, transaction cost, and regional differences are identified and suggested by some studies [9,10] to be necessary elements when designing the demarcation of sectoral coverage. While a large number of studies have quantified the impacts and efficiency of other features of ETS design such as allowance allocation approaches [11–16] and permit prices [17–19], less attention has been paid to quantifying the economic effects of different sectoral coverage design options. Although it is widely acknowledged that sectoral coverage design will affect the economic impacts of an ETS, most relevant studies of China's prospective national ETS are conducted under the assumption that all emissions are subject to a cap. For example, Li et al. [20] and Li et al. [21] assessed the economic and emissions impacts of various carbon prices in China's national ETS, ranging from 30 to 100 Yuan/tonne. Yang et al. [22] analyzed the economic impacts of a full-coverage ETS projected out to 2030, while Zhou et al. [23] evaluated the impacts of a national ETS on provincial economies. Similarly, Zhang et al. [24] and Qi et al. [25] explored the economic and emissions impacts of linking ETS across several countries, without distinguishing the impacts of different sectoral coverage designs. The general conclusion from those studies is that the ETS is a cost-effective policy instrument to reduce CO_2 emissions. However, the assumption of economy-wide sectoral coverage is likely to result in an underestimate of the mitigation costs compared with the second best limited sectoral design that is more likely in practice. In addition, since more reduction responsibility is borne by ETS sectors than the first-best situation, most of which are also heavily air-pollutant intensive, a limited sectoral approach may lead to more air pollutant reduction, i.e., air pollutant co-benefits. If air pollution co-benefits are included in assessments of economic efficiency, it becomes more important to distinguish different sectoral coverage regimes when studying the impacts of ETS, especially for countries like China that are suffering from severe air quality problems.

In this context, this study aims to address a gap in the literature by quantifying the extent to which different sectoral coverage options affect the efficiency of ETS policies, with the target of achieving China's latest INDC. This study presents policymakers more realistic and meaningful insights for mitigation costs of China's INDC targets. Furthermore, beyond the broader conclusion that wider sectoral coverage lowers the mitigation costs of the ETS, the temporal dimension of mitigation costs and the air-pollution co-benefits across different sectoral coverage schemes are discussed in this paper. Each of these has important practical policy implications for China's ETS. The remainder of the paper is organized as follows. Section 2 describes the model, database, and key assumptions used in the study. Section 3 provides a description of the INDC policy scenarios. Section 4 presents the main results. Section 5 provides a detailed discussion of results, limitations of the study, and conclusions.

2. Methods

Computable general equilibrium (CGE) models are widely used to analyze the impacts of climate mitigation policies, especially when detailed econometric evidence of policy performance is unavailable [26]. CGE models are also often advantageous over input-output models because of the ability to capture complex feedbacks as well as being able to consider important price mechanisms and factor substitution effects. This study employs the China Hybrid Energy and Economic Research model (hereafter CHEER), a dynamic recursive CGE model calibrated to the Chinese economy. The CHEER model is an extension of the TDGE_CHN model developed by Wang et al. [27], including numerous updates, such as a more detailed exposition of the production structure, greater technological detail in the electricity sector, greater detail in the labor market, updates to the calibration of the model baseline, and the inclusion of a learning curve for the costs of renewable power generation technologies. Other adjustments are made to enable the model to simulate different climate policy shocks, such as the national cap-and-trade mechanism that is considered in this study.

The CHEER model is calibrated to the 2012 input-output (I-O) table published by China's National Bureau of Statistics (CNBS) [28]. The original 139 sectors are aggregated to 18 sectors, with detailed representation of energy-intensive sectors of the economy (Table 1). Eight energy-intensive sectors (petrochemicals, chemicals, construction materials, iron & steel, non-ferrous metals, paper, electricity, and air

Table 1
Sectors and power generation technologies in CHEER model.

Sectors	Abbr.	Original Sectors Code in IO Table
Electricity	Elec	44,096
Coal and Coking	Coal	06006, 25040
Crude Oil	Oil	07007
Petrochemical Industry	Roil	25039
Natural Gas	Gas	45097, 07007
Agriculture	Agri	01001–05005
Other Mining	Mine	08008–11011
Food	Food	13012–16025
Paper Industry	Paper	22036
Chemical Industry	Chem	26041, 26042
Construction Materials	CM	30052, 30055
Iron and Steel	IST	31059
Non-Ferrous Metals	NFM	32062
Other Energy-Intensive Industries	EII	26043–29051, 30053, 30054, 30056–30058, 31060, 31061, 32063, 33064
Other Manufacturing	OM	17026–21035, 23037, 24038, 34065–42094, 46098–50102
Air Transport	Air	56107
Other Transport	Tran	53104–58109
Services	Serv	43095, 51103, 59110–90139

Table 2
Levelized Costs (USD/MWh) and Generated Power (thousand GWh) by Technologies.

	Coal	Oil	Gas	Nuclear	Hydro	Wind	Biomass	Solar
Investment	5.29	17.6	5.1	14.9	14.6	50	31.87	133.7
O & M	1.64	19.9	2.9	7.8	4.6	21.9	25.955	19.5
Fuel	23.06	50.4	28.1	9.3	0	0	12.93	0
Total Levelized Cost	**29.99**	**87.9**	**36.1**	**32**	**19.2**	**71.9**	**70.755**	**153.2**
2012 Power Generation	3710.4	0.54	109.2	98.3	855.6	103.0	31.6	0.36

transport) are specifically highlighted due to their inclusion in China's national carbon market [7]. Since the extraction of crude oil and natural gas are presented as one sector in the I-O table, the original sector is split according to the cost shares in the GTAP 9 database [29].

2.1. The electricity sector in the CHEER model

In order to improve the technological resolution of the electricity sector, the aggregate electricity sector in the 2012 I-O table was divided into nine subsectors: a power transmission and distribution subsector and eight power generation subsectors (coal-fired, oil-fired, gas-fired, nuclear, hydro, wind, solar PV, and biomass power) following the methodology of Sue Wing [30] and Peters [31]. The 2012 generation shares, by electricity type, are based on data provided by the China Electricity Council [32]. Assumptions on cost shares for each generation technology are based on levelized cost data from the International Energy Agency (IEA) [33] (Table 2).

2.2. Production structure

All sectors are assumed to operate under constant returns to scale and cost optimization. Production in each sector is modeled using nested constant elasticity of substitution (CES) production functions, which are intended to represent the different substitution and complementarity relationships across the various inputs in each sector. There are material inputs that generate the input/output table, as well as factor inputs representing value added.

The production structure of non-electricity sectors is shown in Fig. 1. The energy factors are first combined with the capital-labor aggregation and then combined with other intermediate inputs to generate the final output. Fixed factors, such as land and natural resources, are only required in the agriculture, coal, gas, oil, and mining sectors, and are treated as substitutes for other inputs to control short-term sectoral production. The combination of different inputs is expressed through the CES function based on the specific elasticity of substitution (σ). The fixed proportion input-output relationship, represented by right-angle connections in the figure, is based on the Leontief function, which is a special case of the CES function when σ = 0. Since more than 98.4% of crude oil is used in oil refineries according to China's energy balance table in 2012 [34], crude oil is not regarded as energy input but as an intermediate input in the CHEER model. Additionally, the model also takes into account the fact that not all goods from fossil energy sectors are used as fuels in specific industries. For example, a large proportion of petroleum products from the refined oil sector and coke products from the coal sector are used as feedstock in the chemical industry. As a result, for those sectors, only a portion of energy inputs go to the KLE nest, and the rest are treated as intermediate inputs in the CHEER model.

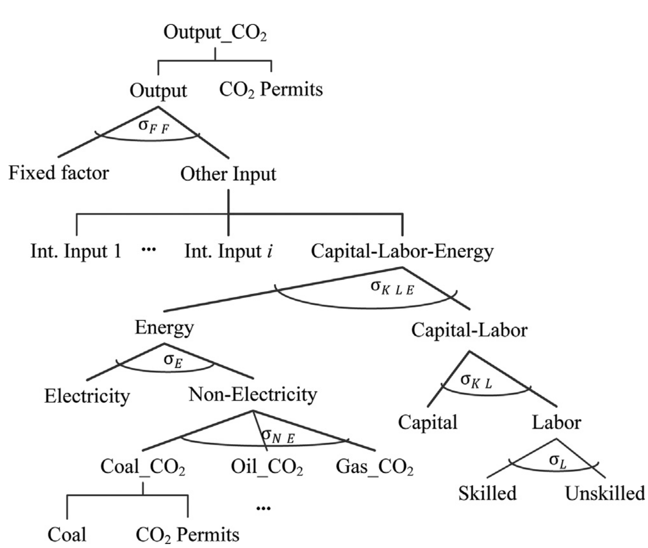

Fig. 1. Nested CES production structure of non-electricity sectors.

The electricity sector has a more complex nested CES production structure (Fig. 2). The top nest of electricity production is a Leontief combination of power generation and power transmission and distribution. Production in power transmission and distribution is assumed to be the Leontief combination of labor, capital and intermediate inputs. The production of aggregate power generation is comprised of eight technologies. Wind and solar PV are imperfect substitutes of baseload generation, due to intermittency. Baseload generation consists of power from conventional fossil fuels, nuclear energy, hydro energy, and biomass with perfect substitution. In the lower nest, each technology has a similar production structure as non-electricity sectors while only non-fossil power technologies need fixed factors as essential inputs.

2.3. Consumption structure

Consumption in the CHEER model assumes a single representative consumer encompassing household and government. All income, including labor compensation, capital remuneration, and tax revenue, is assumed to be distributed to the representative consumer. Disposable income is then allocated between consumption of goods/services and investment. Consumption is modeled using a nested CES consumption function (Fig. 3). The top level assumes a Cobb-Douglas functional form for the tradeoff between consumption goods and investment goods. This assumption is based on the Solow–Swan theory, in which saving accounts for a constant share of total income. At the second level, income is allocated to specific consumption and investment commodities assuming constant elasticities of σ_C and σ_I, respectively. At the third level, a further distinction is made between consumption of non-energy and energy commodities. This is intended to represent the idea that substitution between energy commodities is different than substitution between other consumption goods.

2.4. International trade and market clearing

The treatment of international trade in the CHEER model follows the commonly used Armington assumption, which allows for import and export differentiation between domestic and international markets [35]. Domestic firms allocate domestic production to domestic and international markets using a constant elasticity of transformation (CET) function. Imports are substitutable with domestic goods using a

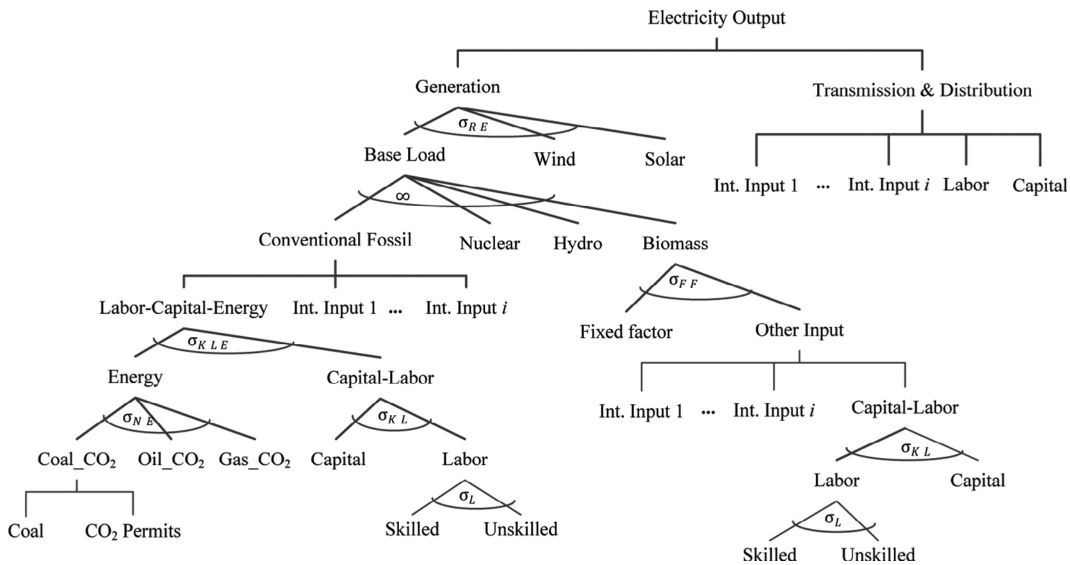

Fig. 2. Nested CES production structure of the electricity sector.

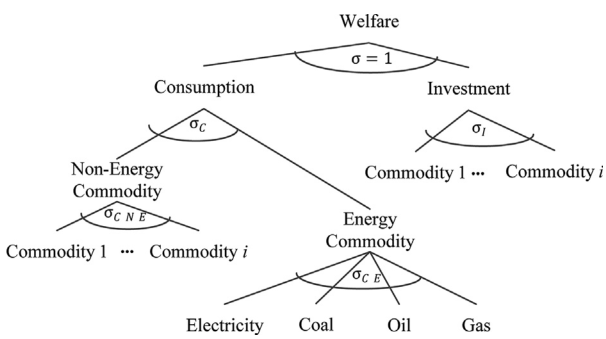

Fig. 3. Nested CES structure of final demand.

CES function. Export demand and import supply are set exogenously following the method of Wang et al. [27].

The equilibrium price of each good is determined by the market clearing condition equating total supply, which includes local production and imports, and total demand, which includes intermediate inputs, consumption, and exports.

2.5. Factor markets

Up to 28 types of labor by gender, region, and educational level can be distinguished in the CHEER model. For this analysis, labor is aggregated into two groups, skilled and unskilled. The supply of each type of labor follows the imperfect market assumption through an endogenous wage curve that reveals the negative relationship between the unemployment rate and real wages [36,37]. This assumption is similar to a labor supply curve but adds the constraint of an active economic population, since the unemployment rate cannot be lower than zero. Due to the inter-sectoral wage differentials and labor's imperfect movement across sectors, CET functions are used to allocate the total labor supply among sectors. The equilibrium wage rate is determined by the labor market clearing condition equating labor supply and demand.

Land and natural resources are distinguished from other capital and are aggregated as fixed factors in this study. The demand for fixed factors is determined by the sector-specific production functions (Fig. 1). The supply of fixed factors is assumed to respond to the price of the fixed factor, which is largely determined by the price of sector output. This is modeled using a constant elasticity of supply function. The supply of non-fixed capital is set constant in each period and is assumed to be perfectly mobile across sectors. Factor market equilibrium of supply and demand determines the prices of capital and fixed factors.

2.6. Emissions accounting

Emissions of CO_2 and two air pollutants, SO_2 and NO_x, are accounted for in the CHEER model. Both CO_2 emissions from fossil fuel combustion and cement production are considered. Emissions factors for fossil fuel combustion are calibrated based on data from the IEA [38]. The emissions factor for cement production is based on Liu [39]. Emissions factors for SO_2 and NO_x are based on the EDGAR V4.3.1 database [40].

The carbon market is implemented in the model by assuming that emissions permits are a necessary input for sectors covered under the policy (Fig. 1). Producers must therefore procure permits corresponding with their own use of fossil fuels and cement in their production processes. The total supply of CO_2 emissions permits is a policy parameter determined based on China's INDCs. Revenues from the emissions permit auction are recycled back to the representative consumer using a lump-sum transfer. Alternative revenue recycling mechanisms have been considered elsewhere and are not included in this analysis [13]. The equilibrium price of CO_2 permits is derived endogenously in the model to equate the supply and demand of permits. Because the focus of this study is different sectoral coverage options for the ETS, a series of ideal conditions, including zero transaction costs and perfectly competitive markets, are assumed in this study for the sake of simplification.

2.7. Dynamic modeling

The CHEER model uses a simple recursive dynamic process which assumes myopic economic agents with static expectations about prices and quantities. The model base year is 2012 and the analytical time frame extends to 2030. Dynamic changes in CHEER originate from three sources: capital accumulation, growth in the labor supply, and productivity changes.

The basic process for capital accumulation is shown in Eq. (1). The current capital stock, K_t, equates the depreciated stock inherited from the previous period, $(1 - \delta)K_{t-1}$, plus gross investment, I_{t-1}.

$$K_t = (1-\delta)K_{t-1} + I_{t-1} \tag{1}$$

Since the I-O table used to calibrate the model shows only data on

new investment and sectoral capital usage, the base year capital stock is estimated indirectly. Additionally, the capital adjustment costs, which are defined as the costs used to convert new added investment into production factors like transportation and installation costs, are considered in the dynamic process. As a result, more complex functions are used in the CHEER model to describe the accumulation process of capital, and a detailed mathematical exposition is described in Appendix A [41–43].

The modeling of labor supply growth is straightforward. As is shown in Eq. (2), the current labor supply, L_t, equals the labor supply in the previous time period, L_{t-1}, adjusted for population growth, g_t^p, and the labor participation rate (LPR), γ_t^p. Both g_t^p and γ_t^p are determined exogenously based on historical trends.

$$L_t = (1 + g_t^p)L_{t-1}\frac{\gamma_t^p}{\gamma_{t-1}^p} \tag{2}$$

Changes in productivity are determined endogenously in order to avoid unrealistic real GDP growth trajectories. Following the methods of Li et al. [44] and Fan et al. [45], the Hicks-neutral Total Factor Productivity (TFP) is set endogenously to calibrate the given real GDP trends from other studies or prospective outlooks. The TFP trend is then fixed to generate the reference scenario and policy simulations.

2.8. Other data and parameters

The 2012 I-O table [28], the 2012 energy balance table [34], and employment data collected from the 6th national population census in China [46] are used to calibrate the CHEER model. The energy balance table is also used to identify the shares of energy products used as feedstock, mainly in the chemical, electricity, oil refining, and coking sectors, as is shown in Table 3.

The majority of the substitution elasticity parameters are taken from TDGE_CHN, with necessary updates according to a recent review of the literature [30,47] (Table 4). Other important data related to the description of scenarios will be presented in the following section.

3. Scenarios

To compare the efficiency of different ETS policy designs, three policy scenarios representing different sectoral coverage of the cap-and-trade program are developed. These include (i) an economy-wide emissions cap scenario (EWA), which covers all non-terrestrial CO_2 emissions in China; (ii) a limited sectoral approach (CSA) reflecting the current policy approach proposed by the Chinese government, and; (iii) an enhanced sectoral approach (ESA) that adds in additional energy-intensive sectors to the CSA scenario. The EWA, CSA, and ESA scenarios cover approximately 100%, 52.1%, and 76.9% of China's national CO_2 emissions, respectively. These three policy scenarios are compared with a Business-As-Usual (BAU) scenario where no emissions constraint is imposed. All four scenarios are briefly summarized in Table 5.

The BAU scenario is constructed using assumptions for population growth, the labor participation rate (LPR), and projected real GDP growth, as described in Section 2.7. Population and LPR assumptions are taken from UNDESA [48]. Real GDP trends, which are used to calibrate total factor productivity growth, are based on a review of the literature [49–51]. The BAU also reflects planned generation targets for wind, solar and biomass electricity prior to 2020, and post-2020 growth of these sources is based on research from the National Development and Reform Commission of China (NDRC) [52]. Autonomous Energy Efficiency Improvement (AEEI), which reflects exogenous improvements in sectoral energy use, is assumed to be 1% per year [27]. These core assumptions for the reference scenario calibration are shown in Table 6. The resulting labor supply growth rate, imputed TFP growth rate, and AEEI growth rate are also used for the three policy scenarios.

For the policy scenarios, CO_2 emissions are restricted based on China's INDC targets. In 2020, China's carbon intensity target is a 40% reduction below the 2005 carbon intensity, increasing to a 60% reduction from 2005 levels by 2030. All mitigation scenarios are required to meet these targets. As noted above, the scenarios differ with regard to the sectoral coverage of the carbon market. In the EWA scenario, the national carbon market reflects an economy-wide approach that includes CO_2 emissions from all production sectors and direct household consumption of fossil fuels. The current sectoral approach (CSA) scenario, which is the narrowest in terms of sectoral scope, includes the eight sectors identified in the NDRC proposal. These include electricity (Elec), petrochemicals (Roil), Paper (Paper), Chemicals (Chem),

Table 3
Shares of energy products used as feedstock.

Sector	Energy commodity	
	Coal	Petrochemical products
Elec		25.2%
Coal	50.4%	
Chem	26.8%	59.6%
Roil		50.8%

Table 4
Core substitution elasticity parameters in CHEER model.

Parameter	Value
σ_{NE}	1
σ_E	0.5
σ_{KL}	Elec-0.81, Coal/Air/Tran/Serv-0.80, Oil/Gas-0.82, Roil-0.74, Agri/Mine-0.68, Other-0.94
σ_{KLE}	0.5
σ_{FF}	Coal-0.7, Oil/Mine -0.6, Gas-0.5, Wind-0.25, Solar/Biomass-0.2, Hydro-0.039, Nuclear- 0.025
σ_C	0.25
σ_{CNE}	0.3
σ_{CE}	0.4
σ_I	0.25
σ_{RE}	1.5

Table 5
Scenario descriptions.

Scenario	Description	Sectors covered	% Covered of China's 2012 CO_2 emissions
BAU	Reference scenario	N/A	N/A
EWA	Economy-wide emissions cap	All sectors	100%
CSA	Current sectoral approach	8 sectors (Elec, Roil, Paper, Chem, CM, IST, NFM, Air)	52.1%
ESA	Enhanced sectoral approach	9 sectors (CSA + EII)	76.9%

Table 6
Assumptions for BAU calibration.

		2012	2015	2020	2025	2030
Macroeconomic Trends	GDP growth rate		7.3%	6.5%	6%	5%
	Population (Billions)	1.355	1.376	1.400	1.408	1.403
	LPR	74.2%	73.2%	70.9%	69.9%	68.6%
	AEEI growth rate	1%				
Installed Renewable Power Capacity (GW)	Wind	61.42	105.33	249.39	434.54	592.47
	Solar	3.41	25.23	104.53	171.72	309.92
	Biomass	7.69	31	58.01	61.2	68.6

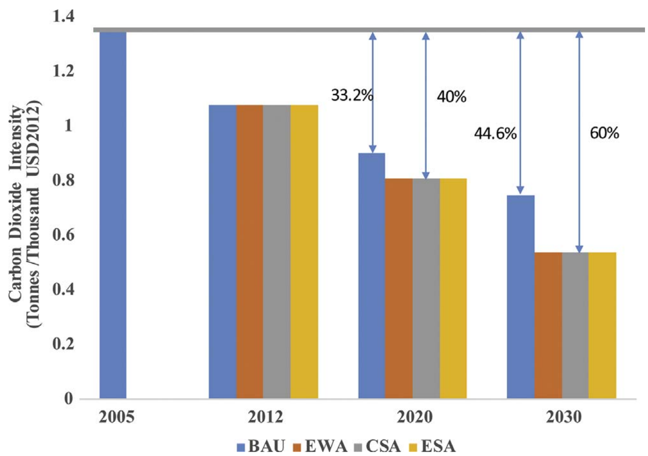

Fig. 4. Trajectory of China's CO_2 Emissions Intensity.

Construction and Material (CM), Iron and Steel (IST), non-ferrous metals (NFM), and Air Transport (Air). In the Enhanced Sectoral Approach (ESA) scenario, all eight CSA sectors are included along with other energy-intensive industries (EII) that represent an additional 25% of China's total CO_2 emissions.

4. Results

This section reports results for all mitigation scenarios. Unless otherwise stated, results are presented as percentage changes from the BAU scenario in 2020 and 2030. The results are presented in three sections: (1) the energy and CO_2 emissions portfolios across scenarios; (2) the mitigation costs, in terms of economic impacts, across scenarios; and (3) the air pollution co-benefits across scenarios.

4.1. Energy and emissions

China's CO_2 intensity, measured as metric tons of CO_2 per thousand US dollars of GDP, significantly decreases in all scenarios in 2030 compared with 2005 (Fig. 4). In BAU, the CO_2 intensity is 33.2% lower in 2020 and 44.6% lower in 2030 than in 2005. In the mitigation scenarios, carbon intensity declines by 40% in 2020 and 60% in 2030, consistent with the exogenous specification of China's INDC commitments in the model. As would be expected for a rapidly growing economy, the gap in carbon intensity between the BAU scenario and the mitigation scenarios increases over time.

Although emissions intensities are identical over time in the mitigation scenarios, the CO_2 emissions pathways differ across scenarios since economic conditions, specifically real GDP, differ between the ETS designs (Fig. 5). In the BAU scenario, the quantity of China's CO_2 emissions continually increases from 9.16 Gt in 2012 to 18.39 Gt in 2030. Despite the increased deployment of renewables and energy efficiency improvements, China's strong economic growth continues to prevent a decline in the growth rate of emissions over time. Emissions grow at a similar rate across all three ETS design scenarios from program implementation in 2017 up until 2020. Post-2020, the emissions trajectories begin to diverge. In particular, the emissions levels for the current sectoral approach (CSA) scenario are approximately 8.6% lower in 2030 than the EWA and ESA scenarios. This is due to the specification of a carbon intensity target, as opposed to a strict emissions cap. As will be discussed later in this section, lower real GDP necessitates lower aggregate emissions levels. Lower CO_2 emissions in the CSA scenario compared to the scenarios with more comprehensive sectoral coverage may seem beneficial, but is important to keep in mind that this is an artifact of considerably slower economic growth.

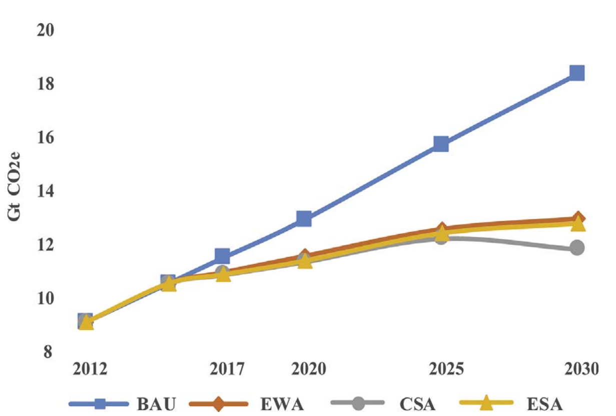

Fig. 5. Trajectory of China's CO_2 emissions in each scenario.

A sectoral decomposition of the emissions reductions identifies the importance of each sector in reaching China's mitigation objectives. Results of the decomposition are shown in Table 7. In the economy-wide mitigation scenario (EWA), the electricity, other energy-intensive industries, and coal sectors account for 32.2%, 23.7%, and 16% of the total emissions reductions in 2030, respectively. In the CSA scenario, where the EII sector is not covered under the ETS design, a much larger share of mitigation is absorbed by the electricity sector. While some mitigation does occur in the EII sector, due to broader general equilibrium effects of the policy, the share of total mitigation for EII falls to 1.8% in 2030. Adding in just the EII sector to the ETS, as under the enhanced sectoral approach scenario, helps to restore the sectoral mitigation profile towards the first-best option of an economy-wide design. Small shares of mitigation that are included in the EWA design but excluded from the ESA design must of course be compensated for, but these adjustments are minimal.

Model results showing primary energy consumption trajectories suggest considerable variability across scenarios, both in terms of overall energy use and the energy mix (Table 8). In the BAU (not shown), China's total primary energy consumption is projected to increase by slightly more than 200% from 2012 to 2030. Due to the expectation in the BAU scenario that non-fossil energy sources will continue to penetrate the Chinese primary energy consumption mix, model results suggest that the share of non-fossil energy resources will increase from 11.9% in 2012 to 15.0% in 2030.

In the policy scenarios, the energy consumption pathway and portfolio are considerably different than the BAU. In all mitigation scenarios, total energy consumption declines relative to the BAU. The largest decrease in total consumption, relative to the BAU in 2030, occurs in the EWA scenario (18.0%), followed by the ESA scenario (15.3%) and the CSA scenario (9.8%). While total primary energy consumption declines, the ETS policies act as a significant stimulus for the non-fossil energy sectors. The wind, solar, and nuclear sectors make up a much larger share of the primary energy portfolio in 2030 compared to the BAU. The stimulus is especially pronounced in the CSA scenario, where the electricity sector must bear a larger proportion of the economy's mitigation burden than the EWA and ESA scenarios. This general result is reaffirmed by noticing that the total 2030 non-fossil share for the EWA and ESA scenarios are 11.3 percentage points and 9.4 percentage points lower, respectively, than the CSA scenario.

As with the primary energy mix, China's electric power sector is also expected to be impacted by the introduction of an ETS policy (Table 9). Overall electric power generation declines by 18.4%, 21.2%, 22.9% in the EWA, CSA, and ESA scenarios in 2030, respectively. This is a result of the higher electricity sector production costs that are assumed to be passed along to consumers. While coal-fired electric power dominates the generation portfolio in the BAU scenario (73.9% in 2030), coal's share of electricity production declines to 57.1%, 19.7%, and 48.9% in the EWA, CSA, and ESA scenarios in 2030, respectively. The overall share of non-fossil electric power production increases most in the CSA scenario, accounting for 17.5% of total electric power generation. Wind

Table 7
Reduction in CO_2 emissions by sector in 2020 and in 2030 (million tonnes).

Sectoral CO_2 reduction (Mt)	Scenario						
	Initial CO_2 emission share	2020			2030		
		EWA	CSA	ESA	EWA	CSA	ESA
Electricity	27.5%	435.6	979.2	587.7	1739.1	3535.3	2252.0
Other Energy Intensive Industries	24.8%	324.1	−37.7	451.3	1281.6	117.7	1612.6
Construction Materials	10.7%	51.6	120.4	86.7	244.6	665.1	331.8
Coal and Coking	8.9%	269.6	182.2	181.4	866.4	656.7	607.9
Iron and Steel	5.7%	59.5	125.0	84.0	222.6	459.8	281.6
Chemical Industry	4.6%	50.8	106.1	69.8	192.3	393.1	239.5
Other Transport	3.2%	14.2	13.9	11.1	82.1	127.9	43.9
Other Manufacturing	3.2%	43.3	2.8	3.3	207.1	125.2	13.8
Services	2.3%	15.9	6.0	4.7	84.9	72.9	15.5
Household	2.0%	11.8	−1.7	−0.7	63.6	−44.3	−23.3
Non-Ferrous Metals	1.4%	18.4	39.2	25.9	75.7	160.0	96.9
Natural Gas	1.3%	24.3	−4.4	−1.8	108.7	2.8	−17.7
Petrochemical Industry	1.0%	7.3	13.2	9.0	29.3	60.2	30.4
Other Mining	0.8%	13.2	−0.2	1.2	71.6	19.2	−2.5
Paper Industry	0.8%	12.2	25.9	16.9	49.2	94.3	61.5
Food	0.6%	8.8	−2.7	−2.2	32.0	−10.7	−10.6
Agriculture	0.5%	3.1	4.2	3.5	25.7	39.3	12.5
Air Transport	0.5%	1.3	4.0	2.8	8.5	30.5	12.7
Crude Oil	0.2%	2.3	0.2	0.5	13.2	9.8	1.3
Total	100%	1367.4	1575.6	1535.1	5398.4	6514.8	5560.0

and nuclear power account for most of this increase in the non-fossil portfolio. Hydro-electric power remains a relatively constant share of the generation portfolio, which is consistent with the understanding that China has already utilized much of its hydro resource potential. Solar penetration remains lower due to the higher assumed costs compared to wind power. The non-fossil electric power shares are similar for the EWA and ESA scenarios, at 40.2% and 47.6%, respectively. Because of the limited ability to spread costs across the entire economy in the CSA scenario, the electric power sector must bear a large percentage of the mitigation burden, which results in more fuel switching towards non-fossil sources. Interestingly, natural gas-fired electric power remains a very small share of China's electric power portfolio in the mitigation scenarios.

4.2. Mitigation costs

In this section, details are presented on the projected economic impacts of the various ETS design scenarios. Emphasis is placed on the impacts on real GDP, sectoral output and prices, and carbon permit prices. In all three mitigation scenarios, real GDP is expected to decline relative to the BAU scenario (Fig. 6). This result is to be expected, as the introduction of a CO_2 emissions constraint will certainly entail economy-wide adjustment costs. What is interesting about this result is the large variation across the three ETS design options. Consistent with previous studies on the adjustment costs of economy-wide cap-and-trade programs, there is a reduction of approximately 2.1% in real GDP in 2030, relative to the BAU, for the EWA scenario. This should be interpreted as a first-best policy outcome for reaching China's CO_2 mitigation objectives. The narrowest sectoral approach to the ETS policy, the CSA scenario, shows a very dramatic reduction real GDP, which reaches a decline of 10.5% in 2030 relative to the BAU. This result suggests that such a limited sectoral approach, which covers only 52.1% of China's CO_2 emissions, will be very costly to the overall economy. Interestingly, adding in the EII sector (ESA scenario), which accounts for an additional 24.8% of China's CO_2 emissions, results in a GDP loss of 3.3% in 2030 relative to the BAU. This suggests that adjustment costs are non-linear with respect to the percent of national emissions covered by the ETS policy. In other words, expanding the sectoral coverage of the policy will likely go a long way in terms of reducing the mitigation costs of the ETS policy. In fact, the ESA scenario's impact on real GDP is not too far off from the optimal mitigation cost found in the EWA scenario.

An examination of the sectoral output changes and prices reveals how the adjustment costs discussed above are distributed throughout

Table 8
Change in primary energy consumption from BAU and non-fossil share of energy mix.

	2020			2030		
	EWA	CSA	ESA	EWA	CSA	ESA
Total	−7.4%	−7.8%	−8.8%	−18.0%	−9.8%	−15.3%
Coal	−13.1%	−15.1%	−14.7%	−36.4%	−41.6%	−38.4%
Oil	−1.4%	−1.5%	−1.8%	−7.0%	−14.9%	−3.9%
Gas	−4.8%	−0.2%	−0.7%	−17.8%	−7.9%	−0.5%
Hydro	3.7%	8.2%	4.9%	8.9%	2.3%	10.2%
Nuclear	13.8%	34.1%	19.3%	53.7%	135.6%	72.9%
Solar	12.4%	−20.7%	−29.6%	55.7%	200.4%	77.7%
Wind	14.8%	20.9%	5.9%	70.2%	239.0%	99.8%
Biomass	8.6%	16.1%	7.3%	33.8%	83.9%	45.9%
Non-fossil share (% of total energy mix)						
BAU	14.4%			15.0%		
Policy Scenarios	16.8%	17.5%	16.5%	25.7%	37.0%	27.6%

Table 9
Percent change of electricity power mix from BAU by generation type.

	2020			2030		
	EWA	CSA	ESA	EWA	CSA	ESA
Total	−6.6%	−17.2%	−10.7%	−18.4%	−21.2%	−22.9%
Coal-fired	−11.4%	−27.0%	−15.8%	−37.0%	−79.0%	−49.0%
Gas-fired	0.0%	11.7%	8.0%	−2.9%	−11.0%	20.1%
Oil-fired	12.0%	26.4%	15.5%	52.4%	64.7%	61.7%
Hydro power	2.5%	5.4%	3.2%	6.6%	18.2%	8.9%
Nuclear power	12.5%	30.7%	17.3%	50.5%	172.3%	70.8%
Solar PV	11.1%	−22.7%	−30.8%	52.5%	247.2%	75.5%
Wind power	13.5%	17.8%	4.1%	66.7%	291.8%	97.4%
Biomass power	7.3%	13.2%	5.6%	31.1%	112.6%	44.1%
Non-fossil share (% of total electric power mix)						
BAU	24.8%			23.9%		
Policy Scenarios	28.4%	32.7%	28.6%	40.2%	77.7%	47.6%

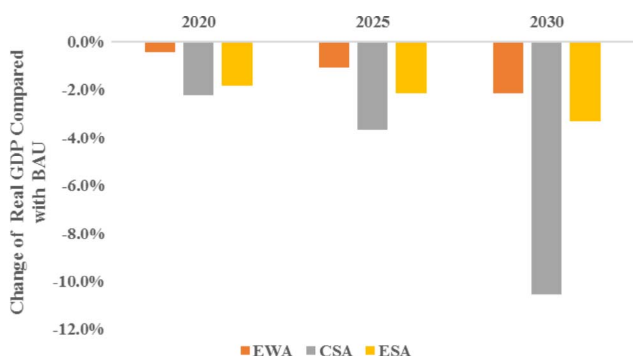

Fig. 6. Real GDP loss compared to the BAU scenario in 2030.

the economy's various sectors. The EWA scenario results in relatively modest price and quantity shifts in most sectors (Fig. 7), although several sectors do see large reductions in quantities relative to BAU, including coal mining (−36.9%), electric power (−14.9%), oil (−9.1%), and refined oil products (−7.1%). Commodity prices for several energy-intensive sectors are expected to increase as the cost of production rises. This includes the construction materials, electric power, iron and steel, and chemicals sectors, for which the model predicts price increases in 2030, relative to BAU, of 32–73%. Results are generally similar for the ESA scenario, with both prices and quantity adjustments being slightly larger than in the EWA scenario. Sectoral adjustment is most pronounced in the CSA scenario, where most sectors experience production declines in excess of 10–20%. In most cases, the decline in production is more than twice the levels predicted in the EWA optimal mitigation scenario. Interestingly, even in energy-intensive sectors not covered by the limited emissions cap (e.g. EII), production declines more than if those sectors were covered under an

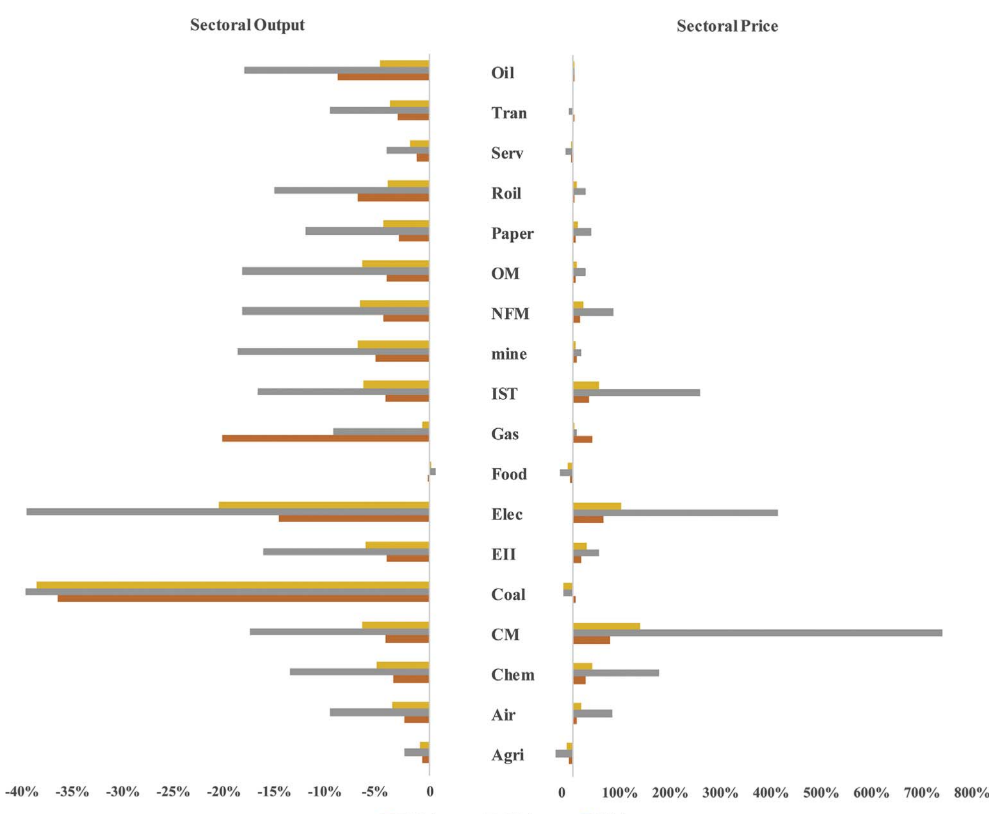

Fig. 7. Changes in sectoral output and prices compared to the BAU scenario in 2030.

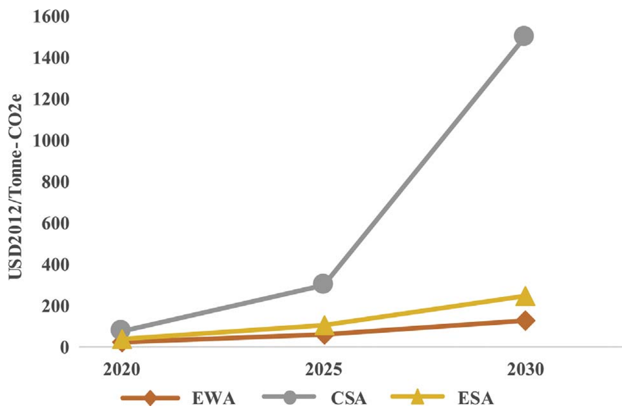

Fig. 8. Trajectory of CO_2 emission permits price.

ETS policy. Similar dynamics are observed for commodity price adjustments, with very large price changes in energy intensive industries that are covered by the emissions trading policy.

CO_2 permit prices represent the marginal cost of mitigation in different emissions constraint scenarios. Consistent with the real GDP and sectoral output results shown above, there is a large deviation in permit prices across scenarios as the emissions intensity constraint becomes more stringent over time (Fig. 8). It is not surprising that the lowest CO_2 price occurs in the economy-wide (EWA) trading scenario, with prices increasing from $23 in 2020 to $130 in 2030. This range in permit prices is generally consistent with other mitigation cost analyses in the literature. At the other end of the spectrum, for the CSA scenario, the model predicts that permit prices will increase from $76 in 2020 to nearly $1500 in 2030. This is a nearly 11.5 times greater in 2030 than permit prices under the EWA scenario. Under the narrow sectoral scope of the CSA design, permit prices increase exponentially relative to the stringency of the emissions intensity constraint. These dramatic permit price impacts from the CSA scenario can be mitigated by adding in other energy-intensive industries (ESA scenario), which results in emissions prices rising from $39 in 2020 to $248 in 2030.

4.3. Air pollution co-benefits

The impacts on SO_2 and NO_x emissions of the various ETS design options are similar to the impacts on CO_2 emissions. Most importantly, results from these simulations affirm that there is a significant co-benefit in terms of air quality improvements from reducing CO_2 emissions. All mitigation scenarios also decrease air pollution. However, air pollution reductions vary considerably across the scenarios. In particular, the CSA scenario results in a larger reduction in emissions as compared to the EWA and ESA scenarios (Table 10). There are two drivers of this result. First, the eight energy intensive sectors covered in the ETS in the CSA scenario are very emissions intensive from an air pollution perspective, accounting for 80.7% and 69.6% of total SO_2 and NO_x emissions, respectively, in 2012. Second, limited sectoral coverage is causing much larger reductions in sectoral output in the eight sectors compared to a more inclusive policy design. While this larger reduction may appear to be an important co-benefit of the limited sectoral approach, it is important to note that the high economy-wide cost of the CSA policy makes this a particularly expensive mechanism for reducing air pollution.

Table 10
Change in air pollution emissions (% difference from BAU).

	2020			2030		
	EWA	CSA	ESA	EWA	CSA	ESA
SO_2	−2.0%	−5.8%	−4.1%	−7.2%	−21.4%	−9.9%
NO_X	−2.2%	−6.3%	−4.2%	−7.5%	−21.9%	−10.3%

5. Discussion

5.1. Main findings with respect to the sectoral coverage of the ETS

This study confirms several important economic concepts that have policy relevance as China embarks on its national emissions trading system following its INDC commitments. Results show that mitigation costs for achieving China's INDC targets using an economy-wide ETS are approximately 2.1% of real GDP in 2030, which is broadly consistent with previous research in this area showing costs of 0.9–4.2% of real GDP [53,54]. While it is accepted that limited sectoral coverage in an ETS design is a second-best mitigation solution, this study affirms that the actual mitigation costs for achieving China's INDC targets through the currently proposed eight-sector ETS, covering 52.1% of China's total CO_2 emissions, may be as large as 5 times higher than that in the optimal economy-wide case. Ignoring this gap in sectoral coverage will lead to a significant underestimation of mitigation costs. This study indicates that the mitigation costs can be reduced to 3.3% of real GDP in 2030 if other energy-intensive sectors, accounting for additional 24.8% of total emissions, are included in the ETS. Therefore, not all emitting sectors need to necessarily be included in China's ETS to approach the first-best mitigation outcome, but leaving out critical sectors can be extremely costly.

In addition to the variation in mitigation costs across sectoral coverage options, it is important to note that the necessity and significance of extending the sectoral coverage in the ETS are exacerbated as the emissions constraints increase over time. Consistent with the concern raised by the IPCC Report [55], this study affirms that there is a non-linear relationship between mitigation costs and the amount of mitigation required. However, an alternative interpretation of this result is that in the near-term, policy-makers may have some flexibility in terms of which sectors are covered under the ETS. Since the mitigation target is less aggressive than in later year, administrators can gain experience running an ETS program with fewer firms in more concentrated industries in the early years. The program can then be expanded to incorporate additional industries and regulated entities as the ETS market matures. Since the other energy-intensive-industries, which are aggregated as the EII sector in this study, include quite a wide range of different industries such as metal products, rubber and plastics, those sectors can be phased in the ETS gradually according to their different marginal mitigation costs.

This study also affirms that an ETS with limited sectoral coverage can create larger air pollution co-benefits than the optimal economy-wide case. According to Yang et al. [56], average economic costs of environmental damages in China due to NO_x and SO_2 are 902–4334 $/tonne and 1006–4832 $/tonne, respectively. The total value of air pollution co-benefits of INDC targets through the proposed eight-sector ETS is 28.5–136.7 billion USD in 2030, which is nearly 3 times larger than the air pollution co-benefits created in the economy-wide case. This result is largely due to the fact that an ETS with limited sectoral coverage will cause greater emissions mitigation in the electric power sector than an economy-wide ETS. This gives policy-makers a justification for starting the ETS from limited sectoral coverage that includes industries with both high CO_2 and air pollution intensities, especially for China that faces severe air quality problems.

5.2. Options for reducing the mitigation costs of a limited coverage ETS

Due to the political and administrative constraints of extending the sectoral coverage in the practice of ETS, it is clear that additional policies are required to ease the economic burden of the ETS as the cap becomes more stringent. Two options include promoting policies to reduce the costs of renewable energy technologies and linking the ETS

to other carbon markets in order to broaden availability of carbon credits.

Because the limited sectoral coverage design proposed for China's ETS relies heavily on mitigation in the electric power sector, investing in renewable energy technologies to reduce their cost is an important complementary policy option. Results in this study suggest that the electric power sector will contribute over 50% of total CO_2 emissions reductions in the limited sectoral coverage ETS scenario. The shift towards non-fossil resources for electricity production plays an important role in the reduction of electric power sector, especially as the sectoral scope becomes narrower. Mittal et al. [53] and Dai et al. [57] suggest that macroeconomic losses could be reduced by increasing installed renewable energy capacity. Although large investment costs are required, the whole economy benefits from lower prices of electricity, fossil energy, and excess emissions permits. Furthermore, the long-run mitigation costs can be reduced by learning effects, which refer to the declining investment costs over time associated with large scale of investment in renewable energy technologies.

Another option for controlling the costs of China's national ETS is to link the market with other international and national ETS programs. China has experience with participating in global carbon markets through projects associated with the Kyoto Protocol's Clean Development Mechanism (CDM). Various studies have suggested linking China's ETS with other ETS programs, including with the EU ETS [58] and prospective global ETS [24,25]. These studies have all found that market integration would lower the mitigation costs of China's ETS. As a result, the policy implication for China is to take active steps in international climate change negotiations towards the integration of international ETS.

5.3. Limitations and Future work

This study has several limitations. First, in order to isolate the importance of sectoral coverage in ETS design, the transaction costs and allocation methods of permits in the national carbon market are not specifically considered. ETS transaction costs are a very important consideration in ETS design, and a more inclusive, or economy-wide, sectoral approach may have high transactions costs that prohibit implementation in the early phases of a new program. Second, several policy measures beyond a cap-and-trade market are identified in China's INDC targets, such as renewable feed-in-tariffs, sustainable forests, green transportation, and building efficiency. These other policies will have interaction effects with a carbon market that are not considered in this study. While multiple policies aimed at achieving a similar objective are generally thought to create deadweight losses, this may not necessarily be the case for a narrower sectoral approach to ETS design. Future work should explore this topic in more detail.

6. Conclusion

This study contributes to the existing literature on optimal carbon mitigation policy by assessing the impacts of various sectoral design options for emissions trading systems used to achieve China's INDC targets. The CHEER model, a computable general equilibrium model of China with detailed representation of electricity and other energy intensive sectors, as well as a complete CO_2 emissions accounting module and carbon market, is used.

Results show several important findings. First, China's INDC targets can be achieved through an economy-wide ETS at an economic cost of 2.1% of real GDP by 2030. This is the optimal approach for minimizing mitigation costs. Second, including only the eight sectors proposed for initial implementation of the ETS in China is likely to result in a much larger mitigation cost than the economy-wide approach, estimated to be as high as 10.5% of 2030 real GDP. These results suggest that previous research focusing on economy-wide sectoral coverage may understand the mitigation costs of China's ETS in practice. Fortunately, this study further indicates that the mitigation costs can be reduced to 3.3% of real GDP in 2030 if other energy-intensive sectors, accounting for additional 24.8% of total emissions, are included in the ETS. As a result, not all sectors are required to get close to the first-best mitigation option if only critical sectors are included. This is a promising finding for policymakers since the political and administrative constraints make it difficult to establish an economy-wide ETS. In addition, the temporal dimension of mitigation costs and air pollution co-benefits under different sectoral schemes of China's ETS give policy-makers some short-run flexibility in terms of phasing in additional industries over time. Finally, this study also suggests that additional policies could be helpful for avoiding potentially high mitigation costs in long term, which include investing in renewable energy technologies and linking to international/national ETS programs.

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Appendix A. Mathematical formulas for dynamic capital accumulation in the CHEER model

As stated in Section 2.7, the capital adjustment costs [35], which are used, for instance, to install new machines and train workers, are considered in the dynamic process of capital accumulation. The basic process is shown as Eq. (A-1) where K_t, J_t and δ represent the capital stock, net investment and depreciation rate in the period t, respectively. Eq. (A-2) shows the relationship between total investment (G_t), net investment (J_t) and capital adjustment costs (A_t). In each period, net investment is used to offset the capital depreciation first, and then the rest is applied to the growth of capital stock. γ stands for the capital growth rate in Eq. (A-3). Eq. (A-4) shows that the total supply of capital in each period (V_t) equals the sum of capital depreciation and capital return ($K_t r$).

$$K_{t+1} = (1-\delta)K_t + J_t \tag{A-1}$$

$$G_t = J_t + A_t \tag{A-2}$$

$$J_t = K_t(\delta + \gamma) \tag{A-3}$$

$$V_t = K_t(\delta + r) \tag{A-4}$$

Following the method from Summers (1981) [36] and Goulder (1989) [37], the capital adjustment costs can be described as Eqs. (A-5a) and (A-5b). ξ is an empirical coefficient representing the threshold for capital adjustment. The adjustment costs will be significant enough to be considered in the process of capital accumulation when the ratio between J_t/K_t exceeds ξ. β is a parameter calibrated from historical data. ξ and β are set as 0.044 and 32.2, respectively, exogenously according to the literature.

$$A_t = \frac{\beta}{2}\left(\frac{J_t}{K_t} - \xi\right)^2 \times K_t \quad \text{if} \frac{J_t}{K_t} > \xi \tag{A-5a}$$

$$A_t = 0 \quad \text{if} \frac{J_t}{K_t} \leqslant \xi \tag{A-5b}$$

In the base year, we can get the relationship shown in Eq. (A-6) by combining Eqs. (A-3) and (A-4). Then, putting Eq. (A-2), Eq. (A-5a) and Eq. (A-5b) into Eq. (A-6), we can get Eqs. (A-7a) and (A-7b). The annual capital growth rate and depreciation rate are assumed to be 0.1 and 0.03, respectively, in the initial period according to Wang (2009) [21]. Since the base year total investment G_0 and base year capital supply can both be taken from the IO table, the capital return rate r can be estimated using Eqs. (A-7a) and (A-7b). The base year capital stock can also be estimated using Eq. (A-3).

$$J_0 = V_0 \frac{(\delta + \gamma)}{(\delta + r)} \tag{A-6}$$

$$G_0 = \frac{V_0}{(\delta + r)} \times \left(\frac{\beta}{2}(\delta + \gamma - \xi)^2 + \delta + \gamma\right) \quad \text{if } \delta + \gamma > \xi \tag{A-7a}$$

$$G_0 = \frac{V_0}{(\delta + r)} \times (\delta + \gamma) \quad \text{if } \delta + \gamma \leqslant \xi \tag{A-7b}$$

Finally, combining Eq. (A-1), Eq. (A-2), Eq. (A-5a) and Eq. (A-5b), we can get the new capital accumulation functions as shown in Eqs. (A-8a) and (A-8b).

$$K_{t+1} = (1-\delta)K_t + \frac{K_t}{\beta}\left[\beta\xi - 1 + \sqrt{1 + 2\beta\left(\frac{G_t}{K_t} - \xi\right)}\right] \quad \text{if} \frac{J_t}{K_t} > \xi \tag{A-8a}$$

$$K_{t+1} = (1-\delta)K_t + G_t \quad \text{if} \frac{J_t}{K_t} \leqslant \xi \tag{A-8b}$$

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